

Υ production in STAR

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Abstract The study of formation and interaction of heavy quarkonia in relativistic heavy ion collisions provides important insight into the properties of the produced medium. Lattice QCD studies show sequential suppression of quarkonia states with increasing temperature; which affirms that a full spectroscopy, including bottomonium, can provide us a thermometer for the matter produced under extreme conditions in relativistic heavy ion collisions and the most direct probe of deconfinement. With the completion of the STAR Electromagnetic Calorimeter and with the increased luminosity provided by RHIC in Runs 6 and 7, the study of Υ production via the di-electron channel becomes possible. We present preliminary results on Υ measurements in pp collisions (from Run 6) along with preliminary results from Au+Au collisions (in Run 7) at $\sqrt{s_{NN}} = 200$ GeV from the STAR experiment.

1 Introduction

The calculations based on lattice QCD predict that strongly interacting systems at very high temperature lead to suppression of heavy quarkonium states. This is due to Debye screening of color charge which provides a potential signature of Quark-Gluon Plasma (QGP) formation in heavy ion collisions [1]. Therefore the production of heavy quarkonia states in pp , pA and AA collisions is an important tool to study the QGP properties [2]. The larger production rates for charmonium states compared to bottomonium states had initiated the studies of charmonium in CERN SPS and further systematically studied at the higher collision energies at RHIC. The observation of charmonium suppression [3, 4] was proposed in relativistic heavy ion collisions. More recently the high energy at RHIC allows the measurement of the Υ states in heavy ion collisions. The lattice QCD studies of quarkonia spectral functions suggest that while the Υ''

melts at RHIC and the Υ' is likely to melt, the Υ is expected to survive [5–7]. Since quarkonia suppression is determined by the plasma temperature and the binding energy, their suppression pattern can be used as a thermometer of the QCD matter [8, 9].

The massive bottomonia states (~ 10 GeV/ c^2) require higher luminosity due to their small production cross-section. Their decay leptons have sufficiently large momenta to be detected above the background processes even in central Au+Au collisions, which enable detection with high efficiency and low trigger rates. In this paper, we report preliminary Υ measurements in $p+p$ collisions (from Run 6) along with preliminary results from Au+Au collisions (in Run 7) at mid-rapidity obtained with the STAR detector.

2 Experimental setup

The quarkonium decay mode for STAR is $\Upsilon \rightarrow e^+e^-$. The main detectors for this analysis are the TPC (Time Projection Chamber) [10] and the BEMC (Barrel Electro-Magnetic Calorimeter) [11]. The advantages of STAR are its large acceptance ($|\eta| < 1$) along with the trigger capabilities of the BEMC and combined electron identification using the TPC+BEMC. The BEMC allows us to trigger on high energy electrons, in particular e^+e^- pairs, even in central Au+Au events.

3 The STAR Υ trigger

The STAR Υ trigger is a two-stage setup which comprises a fast Level-0 (L0) hardware component done in pipeline with the RHIC bunch crossing and a Level-2 (L2) software component (~ 100 – 400 μ s). The BEMC includes a total of 120 calorimeter modules, each subtending an angle of 6° in ϕ direction (~ 0.1 radian) and 1.0 unit in η direction. Sixty calorimeter modules are required to cover

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the azimuthal direction while two cover the η acceptance. Each module is divided into 40 towers with granularity $(\Delta\eta, \Delta\phi) = (0.05, 0.05)$. A Υ trigger (L0) is issued if at least one BEMC tower is above the adjusted threshold of 3.5 GeV (4.08 GeV) for p+p (Au+Au) collisions and the associated trigger patch consisting of 4×4 towers having a total energy above 4.3 GeV.

The L2 trigger is a software trigger which analyzes events at the rate of about 1 kHz. L2 finds towers with a pre-defined energy similar to the L0 threshold and uses them as seeds for the L2 clusters. These seed towers and their two highest energy neighboring towers are combined into a cluster. The clusters are combined in pairs. As the decay channel is e^+e^- , the L2 algorithm takes pairs of clusters and calculates the invariant mass of the cluster pair using the invariant mass formula $m_{ee} = \sqrt{2E_1E_2(1 - \cos\theta_{12})}$, where E_i is the energy of the cluster i (1 or 2) and θ_{12} is the opening angle between clusters. The cosine of the opening angle is obtained from the position of the cluster and the vertex position. Once the pairs are formed and their invariant masses determined, a trigger decision is made if at least one of the pairs is above a present threshold. If the trigger decision is positive the event is flagged to be accepted. It thus aborts the read-out of all detectors if the algorithm does not detect at least one pair with the invariant mass in the mass window $6 \leq m_{ee} \leq 15 \text{ GeV}/c^2$ for p+p and $6.5 \leq m_{ee} \leq 25 \text{ GeV}/c^2$ for Au+Au collisions.

4 Υ analysis and results for p+p and Au+Au collisions

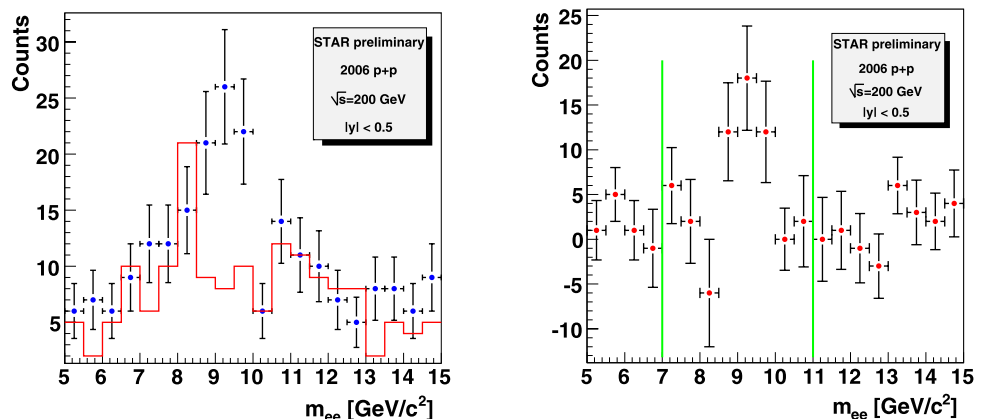
For p+p collisions at $\sqrt{s} = 200 \text{ GeV}$ in 2006, with the full BEMC acceptance, STAR sampled $\sim 9 \text{ pb}^{-1}$ of integrated luminosity. Two different trigger setups were deployed. The preliminary analysis, which focused on one trigger setup with an integrated luminosity of $\int \mathcal{L} dt \sim 5.6 \text{ pb}^{-1}$, was reported in [12]. Electrons were identified by selecting charged particle tracks, where more than 20 out of 45 points are fitted, and whose specific ionization energy loss in the

TPC is greater than 3.5 keV/cm [13]. The selected particle tracks had momenta greater than 3 GeV/c, and were matched to BEMC towers that had energy consistent with the trigger condition, resulting in an implicit E/p cut [12]. The e^+e^- pairs were then combined to produce the invariant mass spectrum. Finally, the like-sign electron pairs were combined to form the invariant mass spectrum of the combinatorial background (using the formula $2\sqrt{N^{++}N^{--}}$ where N^{++} (N^{--}) are the number of positive (negative) electron pairs) which was subtracted from the unlike-sign spectrum as shown in Fig. 4.1.

Since it is not possible to resolve the individual states of the Υ family with the available statistics, the yield reported here is for the combined $\Upsilon + \Upsilon' + \Upsilon''$ states. The total yield was extracted by integrating the invariant mass spectrum from 7 to 11 GeV/ c^2 as shown by the vertical boundaries in the right panel of Fig. 4.1. The invariant mass window was chosen to include $\sim 96\%$ of the signal, determined by simulations. The significance of the signal was estimated to be 3σ . The contribution to the di-electron yield in the Upsilon mass region comes from Drell-Yan and is estimated to be $\sim 9\%$ based on PYTHIA [17]. Additional contributions and their associated systematic uncertainties are under study. We estimate a preliminary cross section at mid-rapidity in $\sqrt{s} = 200 \text{ GeV}$ pp collisions $\text{BR} \times (d\sigma^{\Upsilon+\Upsilon'+\Upsilon''}/dy)|_{y=0} = 91 \pm 28 \text{ (stat.)} \pm 22 \text{ (syst.) pb}$ [12]. The systematic error is dominated by the uncertainty in the integrated luminosity and the current range reflects the total systematic error contribution. The full statistics, including both trigger setups, are under study. The left panel of Fig. 4.2 compares the STAR Υ cross section as a function of rapidity with NLO (next-to-leading-order) CEM (Color Evaporation Model) pQCD calculations with MRST HO PDF with bottom quark mass $m = 4.75 \text{ GeV}/c^2$ and scale $\mu = m_T$ [8, 15, 16]. The right hand side of Fig. 4.2 compares the STAR Υ measurement with data at other energies and with NLO CEM pQCD predictions [8, 15, 16] as a function of centre-of-mass energy.

For Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ in 2007, with the total BEMC acceptance, STAR sampled $\sim 300 \mu\text{b}^{-1}$

Fig. 4.1 Left panel: STAR 2006 $\sqrt{s} = 200 \text{ GeV}$ $\Upsilon \rightarrow e^+e^-$ signal and background in pp collisions. The solid symbols with statistical error bars are obtained by combining the unlike-sign (e^+e^-) pairs. The histogram shows the like-sign background. Right panel: Background-subtracted Υ signal with statistical error bars. The vertical bars mark the integration boundaries for the yield



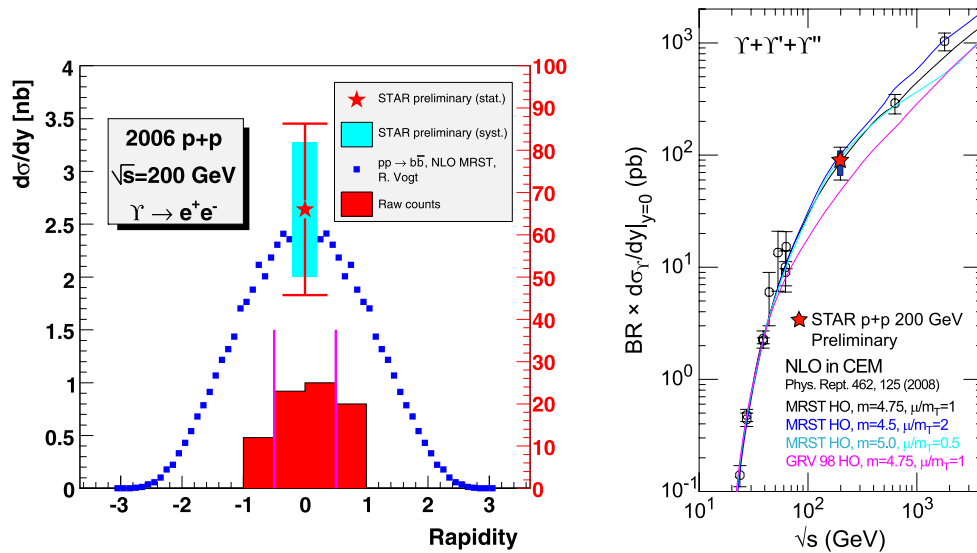


Fig. 4.2 Left panel: STAR $\gamma \rightarrow e^+e^-$ rapidity distribution (left-hand y axis) compared to NLO pQCD calculations [8, 15, 16]. The uncertainties in NLO pQCD calculations are not greater than 50%. The STAR measurement at $y = 0$ is superimposed on the theory curve. The bottom histogram at mid-rapidity gives the number of raw counts (right hand y axis). The vertical bars indicate the integration region,

$|y| < 0.5$. The lower bound of the systematic error is plotted here, since it is still under study. Right panel: The midrapidity $\gamma + \gamma' + \gamma''$ cross section as a function of centre-of-mass energy. The curves are NLO CEM predictions calculated using the parameters given in the legend [8]

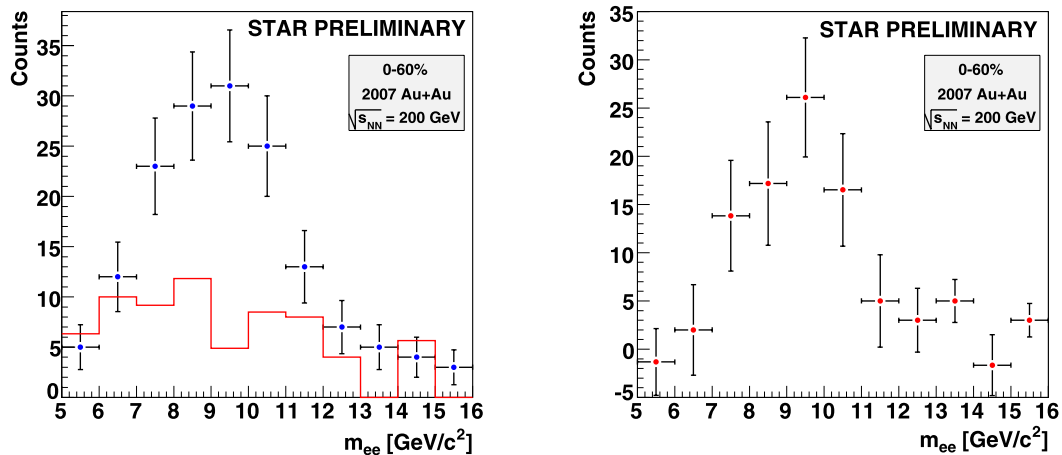


Fig. 4.3 Left panel: STAR 2007 $\sqrt{s_{NN}} = 200$ GeV $\gamma \rightarrow e^+e^-$ signal and background in the 0–60% most central Au+Au collisions. The solid symbols with statistical error bars are obtained by combining

the unlike-sign (e^+e^-) pairs. The histogram shows the like-sign background. Right panel: Background-subtracted γ signal with statistical error bars

($\sim 12 \text{ pb}^{-1}$ of p+p equivalent) of integrated luminosity. Two different trigger setups were used but the preliminary analysis in Au+Au collisions was centered on one trigger setup with the larger integrated luminosity of $\int \mathcal{L} dt \sim 262 \mu\text{b}^{-1}$. The electron identification conditions were similar to those used in the 2006 pp analysis. The electron pair invariant mass spectrum is presented in Fig. 4.3 for 0–60% centrality in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. There is a broad peak at $\sim 10 \text{ GeV}/c^2$ with a significance of 4σ . Both for p+p and Au+Au collisions, the width of the peak is broadened at lower mass. This can be due to electron

bremsstrahlung in the inner tracking material, which includes the silicon tracking detectors near the centre of the detector ($z = 0$), but also includes additional material. For event vertices $|z| > 30$ cm, a fraction of the tracks recorded in the TPC traverse the support structure of the Si detectors. Depending on the exact trajectory of the electron the radiation length varies between 6% and 30%. No additional $|z|$ cuts were imposed to maximize the statistics in the pp and Au+Au analysis. For the Au+Au 2007 analysis the presence of Vertex Position Detector (VPD) imposed an online vertex cut ~ 30 cm on the upsilon triggers and ensured that

the vertex was constrained to be within the acceptance of the inner tracking Si detectors. Broadening at lower mass due to bremsstrahlung is one of the dominant systematic effects and is under study. The trigger efficiency and systematic checks are in progress to estimate the p_T integrated nuclear modification factor, R_{AA} , in the 0–60% most central collisions.

5 Conclusions and outlook

STAR has obtained a preliminary result for the combined $\Upsilon, \Upsilon', \Upsilon'' \rightarrow e^+e^-$ cross section at mid-rapidity in $\sqrt{s} = 200$ GeV pp collisions: $\text{BR} \times (\text{d}\sigma^{\Upsilon+\Upsilon'+\Upsilon''}/\text{d}y)|_{y=0} = 91 \pm 28$ (stat.) ± 22 (syst.) pb [12]. The STAR Υ measurement is consistent with the world data and NLO in the CEM (Color Evaporation Model) pQCD calculations [8]. The full BEMC acceptance and suitable trigger setups are essential for a successful quarkonia program at STAR. Preliminary results for Υ invariant mass in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are presented. The comparative study of the pp and Au+Au data sets to obtain the nuclear modification factor is in progress.

A detailed study of cold nuclear matter effects which includes modification of the initial parton distribution functions is required for quarkonia to separate them from the dense matter effects in heavy ion collisions [8, 14]. The measurements done in pp and in ongoing studies on the d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from Run 8 should allow complete characterization of cold nuclear matter effects (like shadowing, gluon saturation, anti-shadowing, etc.), necessary to quantify the differences between events with and without QGP formation. This will set a proper baseline from which conclusions can be drawn about the effects of the hot medium created in Au+Au collisions.

Extensive measurements of the bottomonium states, the Υ family, is possible at RHIC-II luminosities. A further upgrade has been initiated in STAR to enable large data-samples and higher data rates. This will effectively reduce the front end dead time and allow STAR to make full use of rare-event triggers designed for the Υ s. The integrated luminosity of RHIC-II is expected to significantly boost the Υ yield, up to 6,300 events in pp and 9,700 events in Au+Au collisions [8].

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